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COBALT: TERRESTRIAL FLIGHT TEST OF LANDING NAVIGATION USING LANDER VISION SYSTEM WITH NAVIGATION DOPPLER LIDAR

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COBALT (CoOperative Blending of Autonomous Landing Technologies) is a NASA technology development and test program to advance precision landing capabilities for future soft landers. The COBALT payload demonstrated terrain relative navigation utilizing the Lander Vision System and Navigation Doppler Lidar sensors on the Masten Space Systems Xodiac rocket. In spring 2017, the program culminated in two open-loop free flights to 500 m altitude with down-range diverts of 300 m. The COBALT system performed well, navigating within meters of the Xodiac vehicle's GPS-based solution. This paper outlines details of the navigation filter and its performance during the test campaign.

INTRODUCTION

Guidance, Navigation and Control (GN&C) technologies for Precision Landing and Hazard Avoidance (PL&HA) have been identified by both NASA and the National Research Council as high-priority needs for future robotic and human landing missions.[1,2] The PL&HA capabilities enable safe and precise landing at locations too risky for current GN&C capabilities; such regions include topographically diverse terrain with lander-sized hazards (slopes or rocks), as well as regions with pre-positioned surface assets (cached science samples or human-mission infrastructure).

To address this need, NASA has been developing landing technologies and capabilities through projects including Autonomous precision Landing and Hazard Avoidance Technology (ALHAT)[3–5] and Autonomous Descent and Ascent Powered-Flight Testbed (ADAPT).[6,7] This also includes sensor development for landing navigation with the Jet Propulsion Laboratory (JPL) Lander Vision System (LVS)[8,9] and the Langley Research Center (LaRC) Navigation Doppler Lidar (NDL).[10-13] In 2016, the CoOperative Blending of Autonomous Landing Technologies (COBALT) project was initiated to leverage and combine these efforts with the goal of developing and testing precision GN&C technologies for future soft landers. Operating as a standalone payload, COBALT utilizes the LVS and NDL sensors and fuses the measurements in a navigation filter solution.

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COBALT developed a third generation (GEN3) NDL with improved performance and reduced size, weight and power. NDL provides ultra-precise Line-of-Sight (LOS) velocity plus range measurements and COBALT is the first test campaign of the path-to-flight GEN3 sensor. LVS, which is to be flown on the Mars 2020 mission, is a stand-alone, passive-optical Terrain Relative Navigation (TRN) package comprised of sensors, compute element, image processing and GN&C algorithms. COBALT integrated the NDL and LVS into a self-contained payload for terrestrial flight testing.

The primary objectives of COBALT are to collect a rich dataset of measurements from the NDL and LVS during a propulsive-descent trajectory that is dynamically relevant for future spaceflight applications. At a minimum, this open-loop flight test allows post-flight analysis of sensor and navigation filter performance and a progressive step to closed-loop flight. Further information on the COBALT test campaign objectives, the integration and testing phases, and preliminary results can be found in References 14-16.

Following a series of ground tests at JPL, the COBALT payload was integrated onto the Masten Space Systems (MSS) Xodiac Vertical Take-off and Vertical Landing (VTVL) rocket, shown in Figure 1. A successful open loop flight campaign was conducted in March and April of 2017 testing the payload in a planetary lander relevant dynamic environment. The flight program culminated in two free flights to an altitude of 500 m with downrange diverts of 300 m. The flights were conducted by the MSS and NASA teams at the Mojave Air and Space Port, CA.

The integrated system performed very well, with the TRN+NDL solution being within meters of the Xodiac vehicle's Differential Global Positioning System (DGPS)-based solution. This paper shows that results comparison along with outlining the approach to integrating NDL sensor measurements into the TRN navigation filter architecture, describing the ground and flight test campaign and sharing some of the technical challenges encountered during the program.

Figure 1. COBALT payload on the Masten Xodiac rocket for the 2017 flight campaign

PAYLOAD COMPONENT OVERVIEW

Navigation Doppler Lidar

The GEN3 NDL incorporates several design revisions that increase the dynamic performance envelope and reduce the overall size, weight and power compared to the prototype NDL flown on Morpheus.[13] The NDL consists of a self-sufficient electronics chassis and a fiber-coupled optical head with three rigidly mounted lenses with unobstructed field of view.[10] The GEN3 NDL performance envelope includes a maximum LOS velocity of 200 m/s and a LOS range of over 4 km and provides measurements at a 20 Hz rate with LOS velocity accuracy of 1.7 cm/s and LOS range accuracy of 2.1 m. [10] The NDL and payload components are shown in

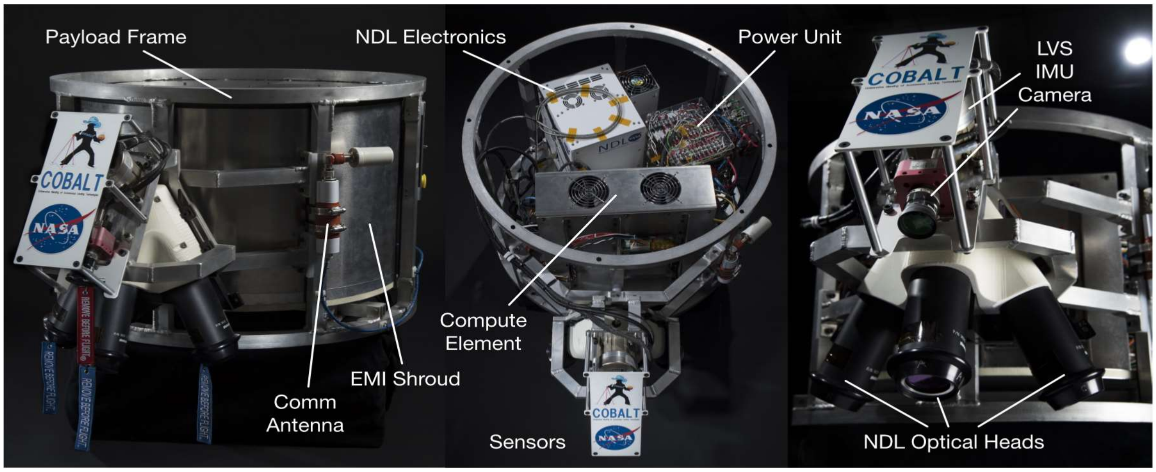

Figure 2.

Lander Vision System and Compute Element

The LVS functionality is carried forward from the successful ADAPT field test campaign.[6-9] The LVS sensors consist of a Northrup Grumman LN200 Inertial Measurement Unit (IMU) and a visible wavelength monochrome camera rigidly mounted to a baseplate. Processing for LVS is done within the COBALT Compute Element (CE), which hosts the LVS TRN algorithms and stores a reconnaissance map used to determine map-relative position estimates.

The COBALT CE is heavily derived from ADAPT and is used to provide sensor data collection, payload timing, vehicle interfacing, data logging, telemetry and communications, and all the computing for the navigation filter state estimation, image processing, and vehicle pose initialization. The CE architecture, like ADAPT, includes an Aeroflex LEON3 compactPCI development board, an Alpha-Data Virtex-5 Field-Programmable Gate Array (FPGA), and an x86-based Single Board Computer (SBC). The FPGA captures and time-stamps payload sensor data, executes the image processing algorithms, combines 400 Hz IMU samples for 100 Hz updates, and receives a GPS-based pulse-per-second signal from the vehicle for timing. The LEON3 board controls the FPGA and executes the COBALT navigation filter algorithms. The SBC logs all test telemetry, performs some algorithm computations, and maintains communication with the remote ground station and a continuous 50 Hz two-way link between COBALT and Xodiac.

Payload Mechanical, Power and Ground Communication System

The COBALT payload frame is circular to match the vehicle structure. The payload electronics are enclosed in a shroud to reduce potential electromagnetic interference between COBALT and Xodiac and provide environmental (dust, moisture and thermal) protection; small fans ensure air-flow during operation. Vibration isolators are incorporated between the payload frame and an internal base plate that holds the COBALT CE, power unit, and NDL electronics chassis. The power unit capacity is 570 Wh, providing the COBALT payload with a 90-minute run-time.

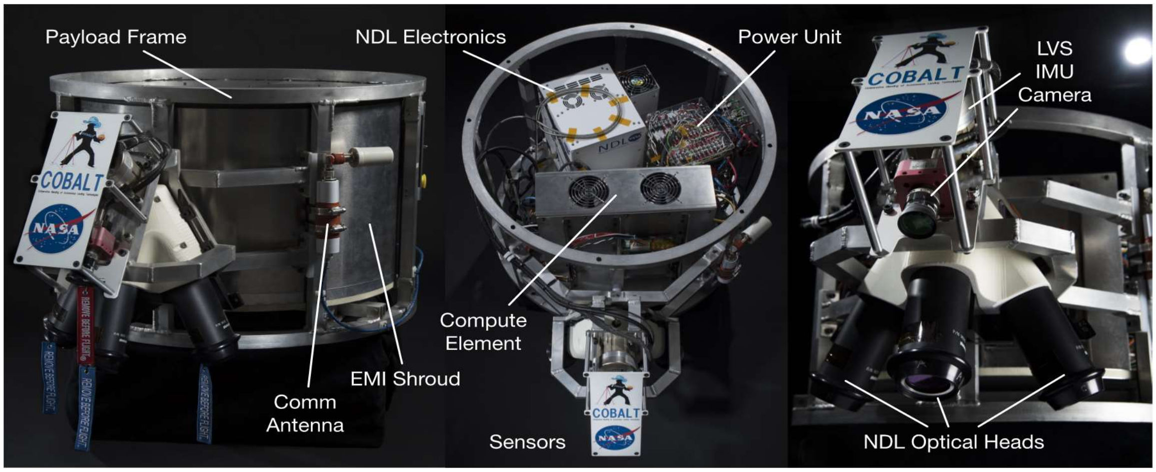

Figure 2. COBALT payload components

The payload wireless radio is used for two-way communication between SBC and the COBALT remote ground station that is approximately 1 km from the launch site. This link is used to initialize and control the payload prior to launch-sequence and although not necessary thereafter, is used to monitor telemetry during flight. The payload to ground communication system uses off-the-shelf Ubiquiti equipment with an omni-directional antenna mounted to the payload frame (

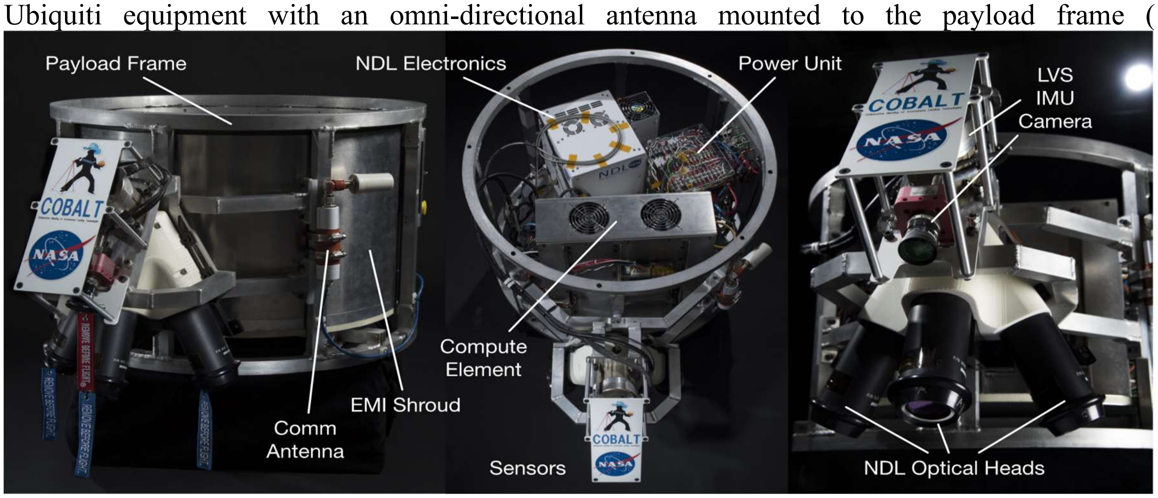

Figure 2). The radios are configured to allow data rates on the order of 8 Mbps at a range of 1.5 km.

MASTEN SPACE SYSTEMS XODIAC VEHICLE

The MSS XA-0.1E-5 (Xodiac) reusable, suborbital VTVL vehicle has been developed to service clients such as the NASA Flight Opportunities (FO) Program, which is funding the flight-test portion of the COBALT project. Figure 1 shows photographs of the Xodiac vehicle with COBALT payload during the open-loop free flight campaign of spring 2017. Xodiac replaces the prior XA-0.1B (Xombie) vehicle and offers an increased payload capacity of 50 kg, higher altitudes and increased down-range profiles. The COBALT campaign is part of its flight envelope expansion, achieving a 500 m altitude and velocities up to 27.6 m/s.

For the COBALT open-loop flight campaign the Masten Xodiac Attitude Control System (ACS) controlled the vehicle using an onboard navigation solution that blends Xodiac IMU data with measurements from a local differential GPS (DGPS) system. This blended ACS solution stays within about 0.3 m of the raw DGPS position estimate and has been used as the reference "truth position" for COBALT post flight analysis.

CONCEPT OF OPERATIONS

The COBALT flight test Concept of Operations (ConOps) was developed to provide an expanded flight test envelope (higher altitudes and velocities) for precision navigation testing, compared to prior NASA precision-landing system testing of the ALHAT/Morpheus[5] and ADAPT/Xombie[6] systems. Additionally, the ConOps is designed to maximize the timeline for collection and blending of NDL and TRN measurements within the navigation filter. The nominal profile and measurement modes flown by COBALT are shown in Figure 3.

The flight profile provides a nominal flight time of 68 seconds from launch until the final 20 m altitude above the landing pad. On takeoff, the vehicle performs a vertical ascent to reach the peak 500-m altitude, followed by a vertical descent with reduced engine thrust to achieve a 25 m/s downward velocity. At maximum downward velocity, a 300 meter lateral divert maneuver is executed to target a pre-determined, down-range landing location.

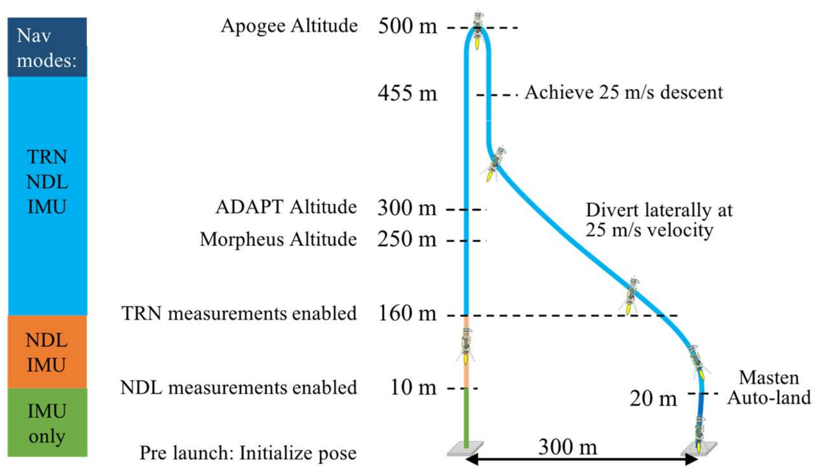

Figure 3. COBALT concept of operations, nominal flight profile and navigation measurement modes.

The COBALT navigation solution is initialized just prior to launch, by using the Pose Initialization and Propagation (PIP) system, developed for ADAPT. The PIP system uses the onboard LVS camera to image an array of GPS-surveyed ground targets and compute a pre-launch vehicle position and attitude. The COBALT navigation filter then propagates the vehicle state using the IMU until valid NDL and/or TRN measurements become available.

NAVIGATION FILTER

The COBALT navigation filter blends 100 Hz delta angles and velocities from the IMU, 20 Hz Doppler velocity and range measurements from the NDL and periodic (0.4-1.0 Hz) state updates from the TRN algorithms to estimate the vehicle position, velocity and attitude. The filter software leverages the multi-task, data-driven SW architecture developed for ADAPT,[6] largely reusing the TRN and IMU algorithms while adding measurement editing and Kalman filter update algorithms to support processing of NDL velocity and range data.

Since the COBALT ConOps calls for processing of NDL measurements at low altitude just after launch, the in-flight TRN batch initialization used on ADAPT was bypassed and the filter is initialized directly into its Extended Kalman Filter (EKF) operating mode. The vehicle state is propagated using IMU alone until the NDL and TRN data become available.

The filter software is "data-driven", sorting the low-latency, time-tagged IMU and NDL data packets into time-order as they arrive from the FPGA. IMU data are used for state propagation between updates while the NDL velocity and range data are used for state updates as they arrive. As for ADAPT, a "cloned state" approach is used for the TRN state updates to accommodate the longer measurement latency induced by image processing (IP).

Nearly all inter-process communication packets in the software are time tagged and logged, including all filter input measurements, the TRN exposure commands and images, the state initialization message from PIP and a comprehensive set of filter diagnostics such as measurement residuals, state corrections, etc.

Replayer

Logging the complete record of filter input data when in flight mode supports a simulation feature built into the ADAPT/COBALT architecture called "Replayer mode". In Replayer mode, a set of up to 64 TRN images are pre-loaded into the FPGA, and files of saved sensor data packets are "replayed" through the filter. Replayer uses timetags saved in the replayed packets to orchestrate delivery of the data to the filter and ensures the pre-loaded images and the IP results arrive at the appropriate simulation time. Because of disk access latency and other data handling constraints, Replayer simulations execute somewhat slower than real-time, but have excellent fidelity, providing essentially bit-level repeatability of real-time flight-mode runs. For COBALT, Replayer was extended to support the logging and replay of NDL data. Replayer simulation capability was a key project asset during the development of the COBALT filter software, during the pre-flight test campaign and for post-flight analysis.

Filter Development

The COBALT navigation filter design builds on ADAPT heritage. Data handling functions to support the NDL were added to the FPGA firmware and to the "sequencer" module that enforces measurement time-order into the navigation filter. Logging functions for NDL data were also added along with a variety of NDL related filter configuration parameters such as measurement noise standard deviations for range and velocity.

Multiple enhancements were also made to the COBALT top-level state machine that coordinates filter initialization, in-flight operation, and post-landing shutdown. The modifications include addition of ground commands to control the NDL sensor, updates and the addition of synchronization to GPS time using a Pulse Per Second (PPS) input from the Masten vehicle.

Development of the COBALT navigation algorithms made extensive use of Replayer mode, the availability of flight data logs from the ADAPT free flight campaign and a simulation of the NDL sensor. A Matlab sensor model of the GEN3 NDL was developed that takes inputs of vehicle position, attitude, and velocity and produces simulated NDL velocity and range measurements with additive Gaussian noise. The model outputs data in a time tagged binary packet format that replicates the NDL serial interface and is compatible with use in the COBALT Replayer simulation.

Early in development, the NDL sensor model was used to process the filter and GPS based state estimates logged during the ADAPT flights, creating "synthetic" NDL data for a realistic flight profile that could be used for initial COBALT Replayer simulations. These ADAPT+NDL Replayer simulations provided an important regression test baseline to ensure existing TRN capability was maintained as NDL functionality was added.

As development progressed, simulations of the planned COBALT trajectory became available and were used to create synthetic data for Replayer simulations. IMU and image data for these runs was created using a developmental version of the Lander Vision System Simulator (LVSS) being developed for the Mars 2020 mission. LVSS can create both IMU data and rendered images based on an input position and attitude time history. COBALT developed a layer of "wrapper" software to orchestrate simulation timing, generate corresponding NDL data using the NDL model and translate between LVSS and COBALT packet formats.

Measurement Editor

A key principle in robust Kalman filter design is to protect the filter from outlier measurements and other non-Gaussian effects. As with most navigation sensors, the GEN3 NDL exhibits some "real-world" behaviors that call for special attention in the filter implementation. The NDL inherently has an operational limit that is a triangular low-velocity/low-range (LVLR) regime below which valid data is not produced. To get an early look at dynamic NDL behavior over ranges closer to flight, COBALT devised a stand-alone test conducted from the top level of a JPL parking structure. In this test, the NDL was mounted on a 2-person all-terrain vehicle (ATV) using a near-horizontal wedge mount. The configuration directed the NDL beams down into the neighboring Arroyo Seco riverbed to achieve a slant range of 300-800 m but with high incidence angle (undesirable). The COBALT CE was used for data logging but navigation was not attempted during the test. Motion of the ATV allowed simultaneous stimulation of the NDL sensor in both velocity and range.

The data of this test provided helpful insight into several NDL measurement characteristics, including occasional random measurement dropouts and non-Gaussian "banding" of the reported range and velocity near specific output values. The occurrence of these effects was highest when operating close to the LVLR regime and may have been a consequence of the test conditions and/or LOS geometry. Based on these observations, several parameter-adjustable features were added to the filter measurement editor and the Matlab model of the sensor was modified to simulate a variety of non-Gaussian effects for use in Replayer simulations. The editor was designed to reject NDL data within a configurable LVLR triangle and handle negative ranges, and exact 0.0 range or velocity values. The filter also includes "sigma" tests for both range and velocity that inhibit the use of measurements with residuals outside a configurable threshold. For COBALT the sigma thresholds were configured to 3-sigma in both velocity and range, providing aggressive rejection of outliers. The velocity and range banding effects are not addressed in the filter, but were largely eliminated before flight by internal calibrations of the NDL sensor.

The final flight configuration of the filter includes global enables for both TRN and NDL state updates along with parameters to start and stop state TRN or NDL updates at a specific estimated altitude above ground level. These features were used during the COBALT free flights to inhibit NDL updates until well outside the LVLR regime and to avoid making TRN updates based on low altitude, low feature count images. The parameters were configured to start accepting NDL data at 10 m altitude and continue through landing. TRN updates were enabled at 160 m altitude, ensuring robust image feature counts at the initial TRN state update.

PRE-FLIGHT PAYLOAD TESTING

In preparation for the flight campaign, a calibration and test program for the COBALT payload was conducted at JPL. Calibration activities included estimating a CAHVOR camera model based on calibration target images and performing laser scanner metrology of the alignment between the LVS camera and the IMU.[17] Following integration of the NDL, its alignment was measured relative to the IMU. Final alignment activities were completed after installation of the assembled COBALT payload onto Xodiac, measuring the alignment between the COBALT IMU and the Xodiac IMU.

To verify interfaces, develop flight procedures and demonstrate filter operation, a series of payload operational tests were performed. A "wall test", executed prior to integration of NDL, used a wall-mounted Mars image (and corresponding onboard map) to exercise TRN feature tracking and navigation algorithms. To simulate processor loading and exercise the NDL bi-directional serial interface, a "loopback" approach was used, with the COBALT CE transmitting a simulated NDL serial stream and looping it back to the CE as an input via a special test harness.

To evaluate phasing and timing latency between the IMU and NDL, a "swing test" was conceived. In this test, the integrated payload was suspended above a concrete floor and allowed to swing in an arc, producing a sinusoidal signature in both IMU and NDL data. The lack of precision state initialization made the results difficult to interpret with enough precision to verify timing. A non-destructive "bump test" was then used to confirm timing latency between IMU and NDL to the desired precision.

The most flight-like test configuration was a series of "ATV" tests. In these tests, the integrated COBALT payload was mounted to the ATV and the payload was operated through a flight-like sequence of activities including PIP initialization, navigation in a dynamic environment using blended IMU and NDL data and periodic acquisition of TRN images. The ATV tests exercised the sensor interfaces and the onboard processing with only a few exceptions. The very short range from NDL to the road surface meant the NDL range data was not usable for navigation. Range updates were instead tested using Replayer. TRN only verified the interface as there were was no map of the road surface and consequently no feature correlation with it images or state updates. TRN functionality was verified in Replayer using ADAPT flight images.

As described above, the NDL sensor has a low-range/low-velocity regime in which the output data are not valid. As a result, the NDL measurements were not valid with the ATV at low speed or stopped. However, with the ATV in motion, valid NDL Doppler velocity data was produced and accepted by the filter. The NDL Doppler velocity measurements provided a dramatic improvement in navigation performance compared to IMU-only runs, with the navigation errors over a 5 min drive dropping from km to meters.

The ATV test runs validated planned operational procedures and demonstrated successful navigation of the COBALT payload using IMU+NDL data. Combined with Replayer simulations using the nominal COBALT trajectory, the pre-flight tests provided confidence to move forward into the flight test program. However, in hindsight, because of the inherent intermittent NDL data validity and lack of TRN state updates, the ATV tests did not achieve full flight-like processor loading for the full flight duration. This shortcoming of the test program will be discussed further in the next section.

FLIGHT TEST CAMPAIGN

The COBALT flight campaign began with a series of tethered flights. These tests were intended to provide a shakeout of the operational procedures and the PIP filter initialization process, demonstrate IMU-only navigation by the COBALT filter and verify nominal operation of the Masten Xodiac vehicle with the operating COBALT payload. An anomaly during the first tether test interrupted IMU data delivery just before liftoff and prevented PIP initialization of the COBALT filter. After some investigation, the root cause was traced to an idiosyncrasy of the FPGA that handles IMU data and a fix was implemented in COBALT software without modifying the FPGA firmware. The IMU data was successfully logged during the flight allowing a Replayer reconstruction that gave confidence of COBALT filter operation. Subsequent tether flights were successful. As was expected, NDL data was intermittent, with the sensor entering its operational range/velocity envelope only for a few seconds as the Xodiac vehicle executed commanded translations in hover at its low altitude on the tether.

Following the successful tethered flights, two Xodiac free flights to an altitude of 500 m were conducted on the Masten test range in Mojave, CA. During the first flight the COBALT navigation filter was configured to accept NDL velocity and range measurements starting at a navigated altitude of 10 m above the Launchpad. PIP initialization was successful and NDL data quickly became valid as the sensor entered the operational range/velocity envelope. The Xodiac vehicle executed the planned trajectory successfully, landing 300 m downrange, however post-flight evaluation of COBALT logged telemetry showed an issue had occurred with the payload during flight. The TRN imaging cadence was much lower than predicted and there were significant gaps in the IMU telemetry logs of the flight.

Investigation into the unexpected behavior suggested that the modifications to add the NDL measurements had caused the COBALT processor to become slightly overloaded, causing overruns on some lower priority tasks including telemetry logging. Available data indicated that the navigation filter had operated as expected, receiving continuous IMU data, performing both NDL and TRN measurement updates and producing valid state estimates. Unfortunately, the low imaging cadence caused degraded LVS performance and the partial loss of logged IMU data prevented a Replayer reconstruction of the flight.

Subsequent ground testing using a special diagnostic build of the COBALT software was able to duplicate the observed symptoms and comparison with data from the ATV tests showed that the overload was likely triggered by the extended duration of continuous, valid, 20 Hz NDL data seen during the flight. The pre-flight testing had failed to reach full load conditions on the processor. During ATV testing, the low speeds near stop signs on the drive circuit had caused the NDL data to become invalid for 10's of seconds, allowing the processor backlog to clear, hiding the problem. A contributing factor was the lack of clear telemetry reporting the instantaneous processor loading.

Since the primary flight test goal was to acquire a coherent IMU, TRN and NDL dataset (Replayer simulations could be used post-flight to evaluate blended filter performance), the second free flight was conducted with NDL measurement updates disabled in the filter. This workaround substantially reduced processor loading and was accomplished via available parameter settings, avoiding additional unplanned tether flights. The Masten Xodiac vehicle executed the flight profile flawlessly. No signs of processor overload were observed during the flight and all NDL, IMU and TRN data was successfully logged. The TRN imaging cadence was nominal and the filter navigated as expected using IMU and TRN data.

POST FLIGHT ANALYSIS

As planned, Replayer runs were performed following the flight to evaluate the effect of NDL data on the navigation solution. Processor loading from handling the NDL data is not an issue for Replayer runs because the software runs in a non-real-time mode with Replayer enforcing the correct packet delivery order.

Figure 4 shows navigation errors in an East, North, Up (ENU) reference frame for a baseline run that includes IMU, TRN and NDL velocity and range data in a blended solution. The "truth" reference assumed is the DGPS-anchored Xodiac ACS solution used to control the vehicle. An observed 2.6 m offset between the PIP position estimate and the reported initial Xodiac ACS position has been removed, making position error zero at filter initialization.

The quadratic trend in the position error between filter start at T=0 and NDL data enable at T=22 s is interpreted as gravity compensation error. During this period COBALT state is being propagated by IMU alone and initial PIP attitude error causes incomplete removal of the local gravity from the IMU accelerometer data.

The effect of the NDL and TRN data enables can be seen at approximately T=22 s and T=38 s, respectively. Between those times the COBALT solution is being estimated using IMU+NDL. After TRN images commence, a full IMU+TRN+NDL solution is available. The first accepted state update from TRN causes a ~1.9 m horizontal change in the COBALT estimated position. This is interpreted as residual map-tie error between the onboard map in use by TRN and the Xodiac DGPS.

Maximum position error for this baseline run is about 4 m. The error in COBALT estimated velocity relative to Xodiac ACS is about 0.25 m/s per axis. The velocity errors are dominated by a signature of the vehicle total acceleration, suggesting there may be some remnant time synchronization offset.

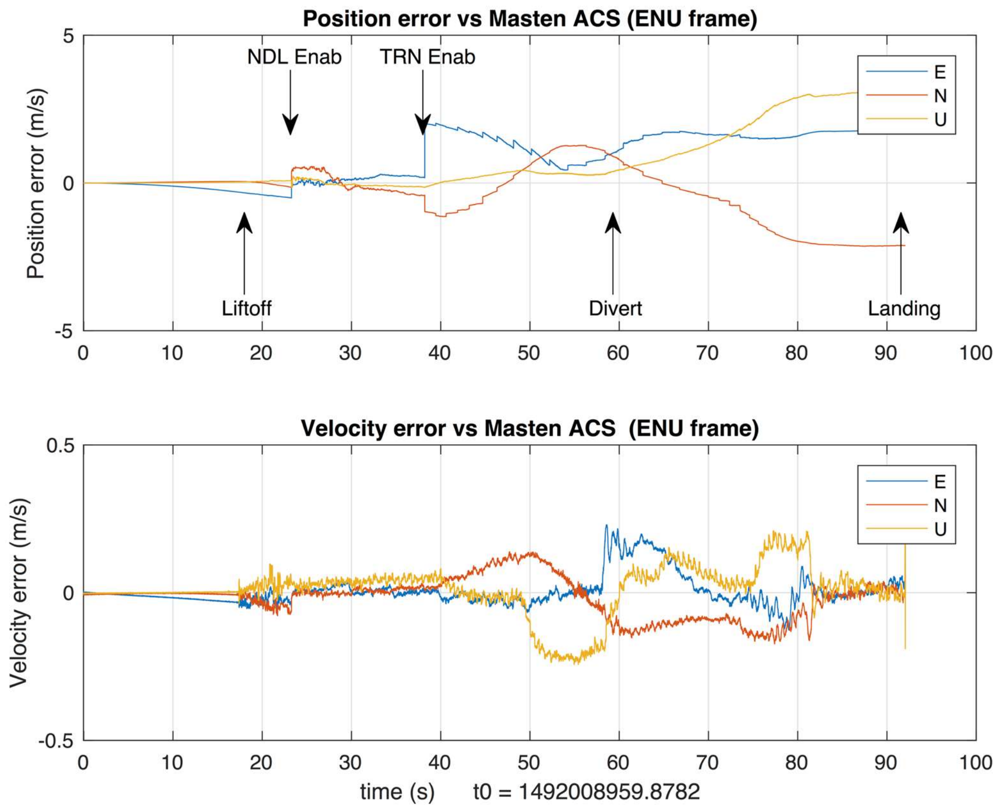

Figure 4. Baseline COBALT performance using IMU+TRN+NDL

Processing of the NDL range measurements inside the COBALT filter assumes the NDL is operating over a planar surface. In the baseline Replayer run above, the NDL surface is assumed horizontal, however the COBALT filter design includes parameters that allow for a non-horizontal NDL surface. Experiments with the NDL surface normal revealed that navigation performance were improved somewhat by adding a ~1 deg surface slope, which is approximately consistent with the Masten test range local terrain. It seems likely that additional improvement to NDL range updates might be possible by evaluating the terrain altitude at each beam footprint using a digital elevation map.

Figure 5 shows estimated COBALT navigation performance using sloped terrain and compensating for the estimated TRN map-tie error. The maximum position error magnitude is reduced to about 1.8 m.

Figure 6 shows details of NDL range measurements. The upper plot compares measured range to the filter predicted measurements and shows excellent agreement through most of the flight. The outage from T=54 s to T=60 s coincides with execution of the vehicle pitchover for the divert maneuver and is believed to be caused by interaction between the NDL beams and thermal/atmospheric effects of the Xodiac rocket plume. During this period, the NDL was flagging the beam-B data as invalid.

The lower plot of Figure 6 shows the magnitude of the range residual compared to the filter predicted residual error (residual ratio). Some non-Gaussian and outlier data can be seen just after the beam-B data outage ends and again just before touchdown when the NDL is operating near the low-velocity/low-range regime. The settings of the range residual measurement editor in use prevent state updates for measurements with residuals larger than 3-sigma. The NDL team has performed detailed analyses of the sensor performance in Reference 10.

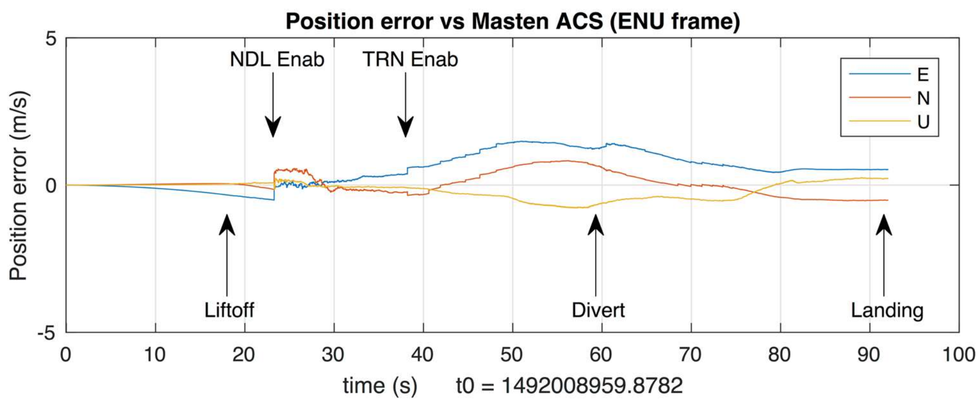

Figure 5. COBALT position performance with TRN map-tie and mean terrain slope corrected

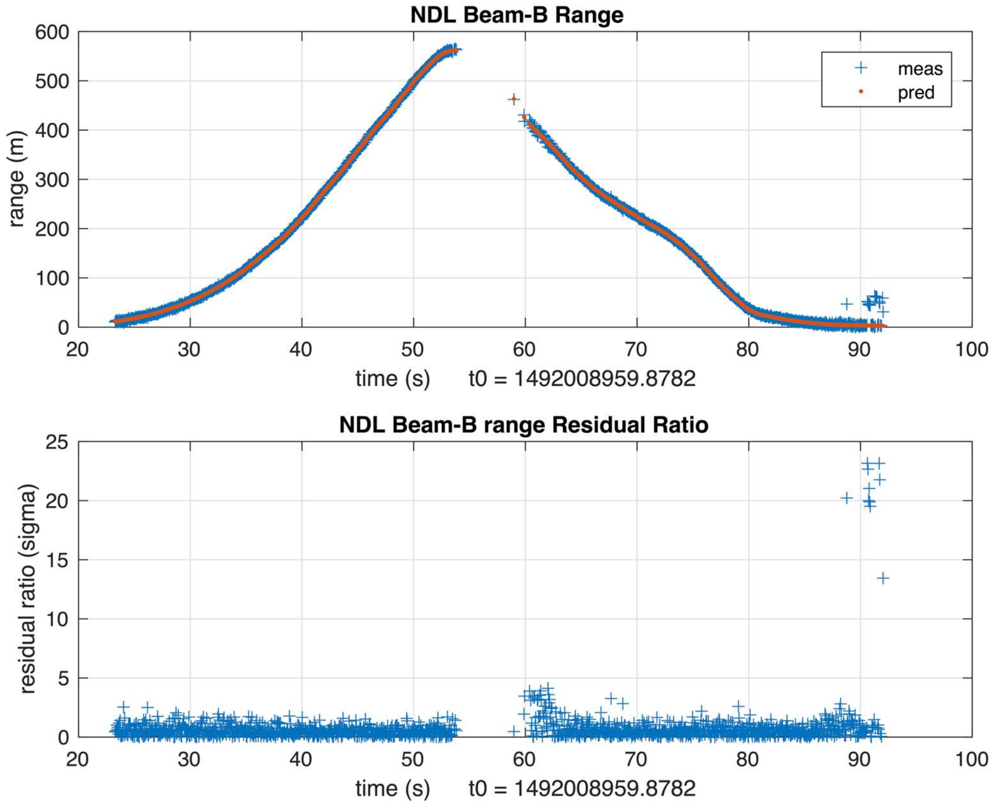

Figure 6. NDL Range Measurements and Measurement Residuals

CONCLUSION

The COBALT project accomplished a successful flight test campaign, collecting an excellent dataset of sensor data and culminating in a demonstration of an integrated TRN+NDL navigation filter. Processor performance limitations presented challenges and prevented use of the NDL data in flight but post-flight reconstruction using logged IMU, TRN and NDL data performed well with position errors below 2 m compared to the Xodiac DGPS-based position estimates. The system provides a promising approach to navigation for planetary landing, combining advantages of map-referenced Terrain Relative Navigation with direct measurement of velocity and range using NDL.

ACKNOWLEDGMENTS

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REFERENCES

[1]Steering Committee for NASA Technology Roadmaps; National Research Council of the National Academies, NASA Space Technology Roadmaps and Priorities: Restoring NASA's Technological Edge and Paving the Way for a New Era in Space, The National Academies Press, 2012.

[2]Office of the Chief Technologist, 2015 NASA Technology Roadmaps, NASA, 2015.

[3]Epp, C. D., Robertson, E. A., and Carson III, J. M., "Developing Autonomous Precision Landing and Hazard Avoidance Technology from Concept through Flight-Tested Prototypes," Proc. AIAA GN&C Conference, AIAA 2015-0324, Kissimmee, FL, Jan. 5–8 2015.

[4]Trawny, N., Huertas, A., Luna, M. E., Villalpando, C. Y., Martin, K., Carson, J. M., Johnson, A. E., Restrepo, C., and Roback, V. E., "Flight testing a Real-Time Hazard Detection System for Safe Lunar Landing on the Rocket-Powered Morpheus Vehicle," Proc. AIAA GN&C Conference, AIAA 2015-0326, Kissimmee, FL, Jan. 5–8 2015.

[5]Carson III, J. M., Robertson, E. A., Trawny, N., and Amzajerdian, F., "Flight Testing ALHAT Precision Landing Technologies Integrated Onboard the Morpheus Rocket Vehicle," Proc. AIAA Space 2015 Conference & Exposition, Pasadena, CA, August 2015.

[6]Trawny, N., Benito, J., Tweddle, B., Bergh, C. F., et. al., "Flight testing of terrain-relative navigation and large-divert guidance on a VTVL rocket," Proc. AIAA SPACE 2015 Conference & Exposition, August 2015.

[7]Scharf, D., Regehr, M., Dueri, D., Acikmese, B., Vaughan, G., Benito, J., Ansari, H., Aung, M., Johnson, A., Masten, D., Nietfeld, S., Casoliva, J., and Mohan, S., "ADAPT Demonstrations of Onboard Large-Divert Guidance with a VTVL Rocket," Proc. IEEE Aerospace Conference, March 2014.

[8]Johnson, A. E., Cheng, Y., Montgomery, J., Trawny, N., and Zheng, B. T. J., "Real-Time Terrain Relative Navigation Test Results from a Relevant Environment for Mars Landing," Proc. AIAA GN&C Conference, AIAA 2015-0851, Kissimmee, FL, Jan. 5–8 2015.

[9]Johnson, A. E., Cheng, Y., Montgomery, J., Trawny, N., Tweddle, B. E., and Zheng, J., "Design and Analysis of Map Relative Localization for Access to Hazardous Landing Sites on Mars," Proc. AIAA GN&C Conference, AIAA 2016-0379, San Diego, CA, Jan. 4–8 2016.

[10]Pierrottet, D.F., Hines, G., Barnes, B., Amzajerdian, F., Petway, L., Carson, J.M., "Navigation Doppler Lidar Integrated Testing Aboard Autonomous Rocket Powered Vehicles," (AIAA 2018-0614) Proc. AIAA SciTech Kissimmee, FL, Jan. 8-12 2018.

[11]Pierrottet, D. F., Amzajerdian, F., Petway, L. B., Hines, G. D., and Barnes, B., "Field Demonstration of a Precision Navigation Lidar System for Space Vehicles," Proc. AIAA Guidance, Navigation, and Control Conference, Boston, MA, August 2013.

[12]Amzajerdian, F., Pierrottet, D., Hines, G., Petway, L., and Barnes, B., "Fiber-based Doppler Lidar Sensor for Vector Velocity and Altitude Measurements," Frontiers in Optics 2015, OSA Technical Digest, 2015.

[13]Amzajerdian, F., Hines, G. D., Petway, L. B., Barnes, B. W., and Pierrottet, D. F., "Development and Demonstration of Navigation Doppler Lidar for Future Landing Mission," Proc. AIAA Space 2016 Conference & Exposition, Long Beach, CA, September 2016.

[14]Carson III, J. M., Seubert, C.R., Amzajerdian, F., Bergh, C., Kourchians, A., et. al.,"COBALT: Development of a Platform to Flight Test Lander GN&C Technologies on Suborbital Rockets," Proc. AIAA SciTech Forum and Exposition, Gaylord, TX, Jan. 9–13 2017.

[15]Carson III, J. M., Seubert, C. R., Amzajerdian, F., Villalpando, C. Y., Bergh, C., O'Neal, T., Robertson, E. A., Hines, G. D., and Pierrottet, D. F., "COBALT: a Payload for Closed-Loop Flight Testing of ALHAT GN&C Technologies on Terrestrial Rockets," Proc. AIAA Space 2016 Conference & Exposition, Long Beach, CA, September 2016.

[16] Restrepo, C. I., Carson III, J.M., Amzajerdian, F., Seubert, C. R., Lovelace, R.S., McCarthy, M.M., Tse, T., Stelling, R., Collins, S.M., "Open-Loop Performance of COBALT Precision Landing Payload on a Commercial Sub-Orbital Rocket," (AIAA 2018-0613) Proc. AIAA SciTech Forum and Exposition, Kissimmee, FL, Jan. 8-12 2018.

[17]Di, K. and Li, R., "CAHVOR camera model and its photogrammetric conversion for planetary applications," Journal of Geophysical Research, Vol. 109, No. E4, April 2004.